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(54) A folded spiral MRI gradient coil

(57) An X- or Y- gradient coil of a magnetic resonance imaging apparatus comprises a folded spiral of an electrically conductive material, which includes a first set of loops 1 of conductive material disposed on an inner curved surface, e.g. a cylinder, and a second set of loops 2 of conductive material disposed on an outer curved surface. Selected loops of the outermost part of the first set of loops are connected to selected loops of the second set of loops by loop-connector parts 3 extending between the curved surfaces at the fold.

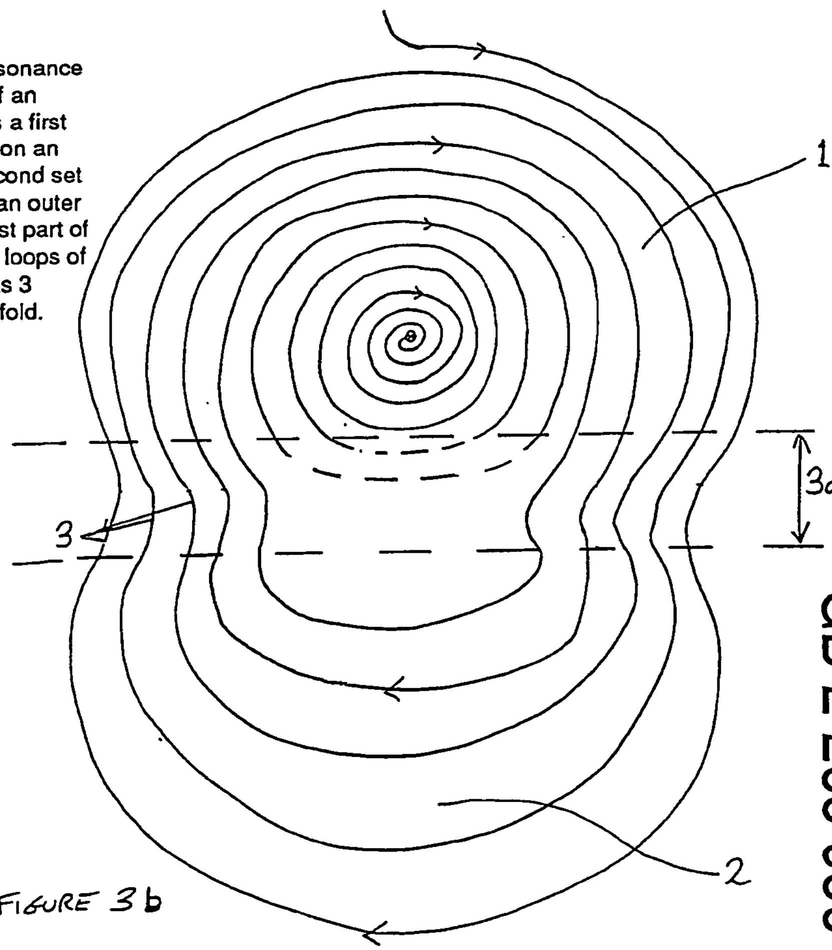

FIGURE 3b

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

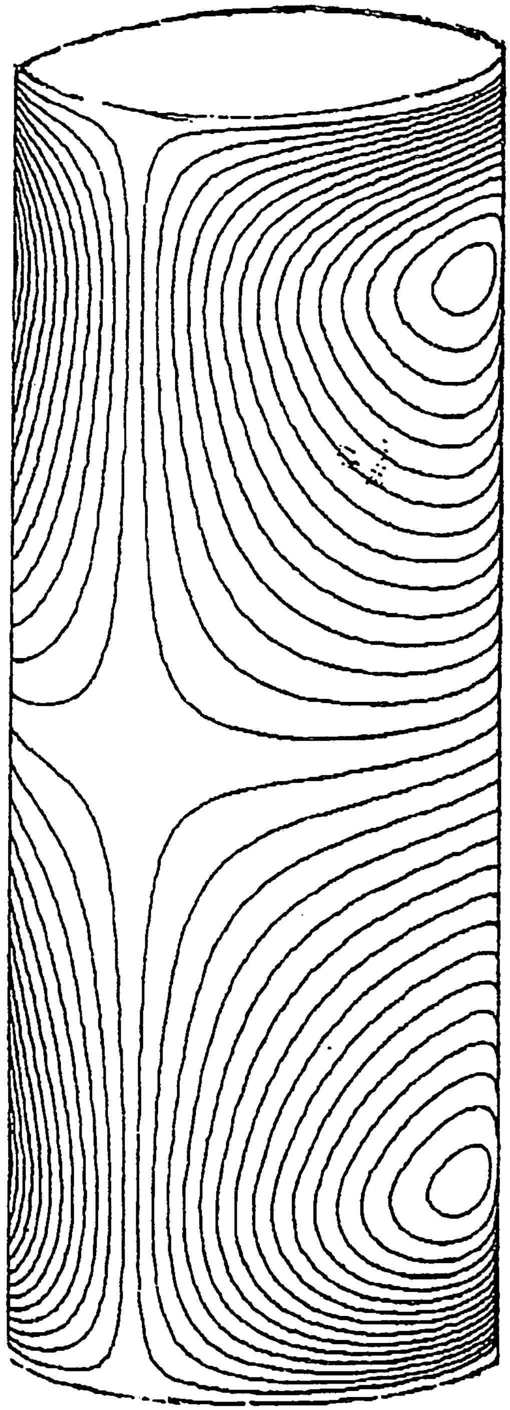

Figure 1

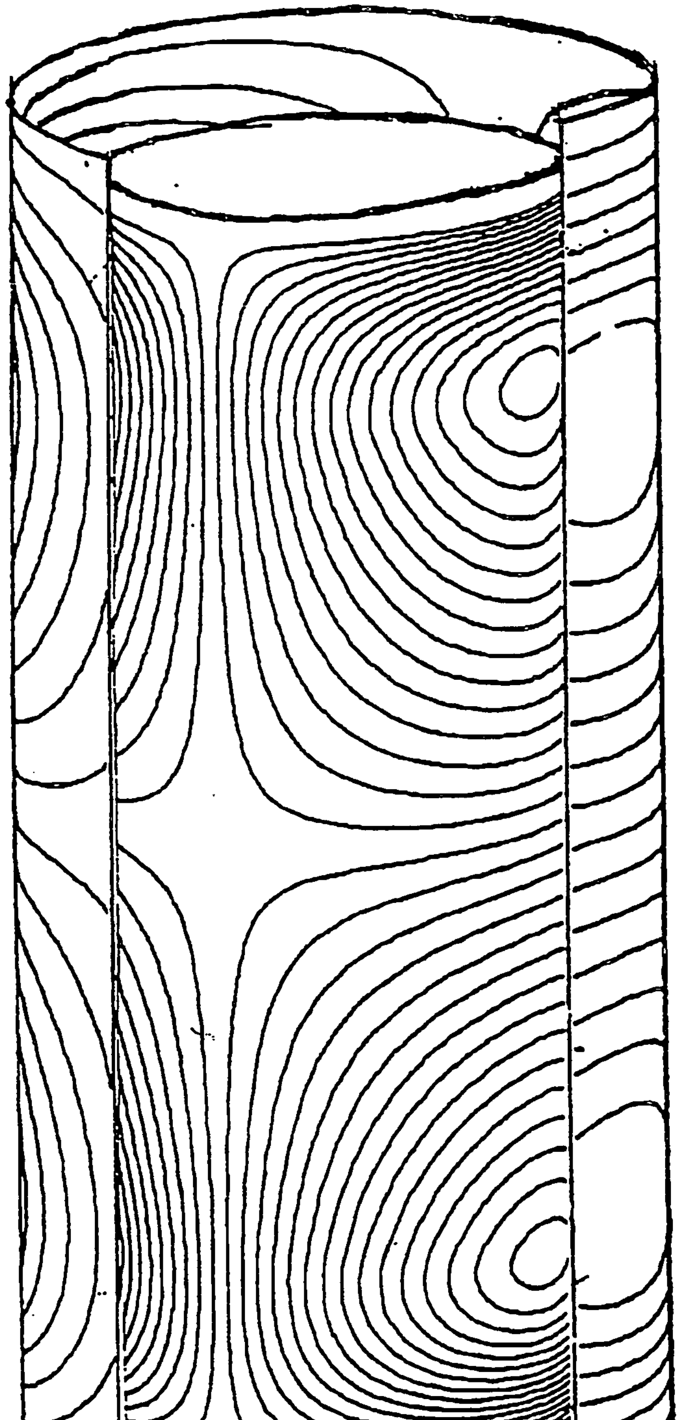

Figure 2

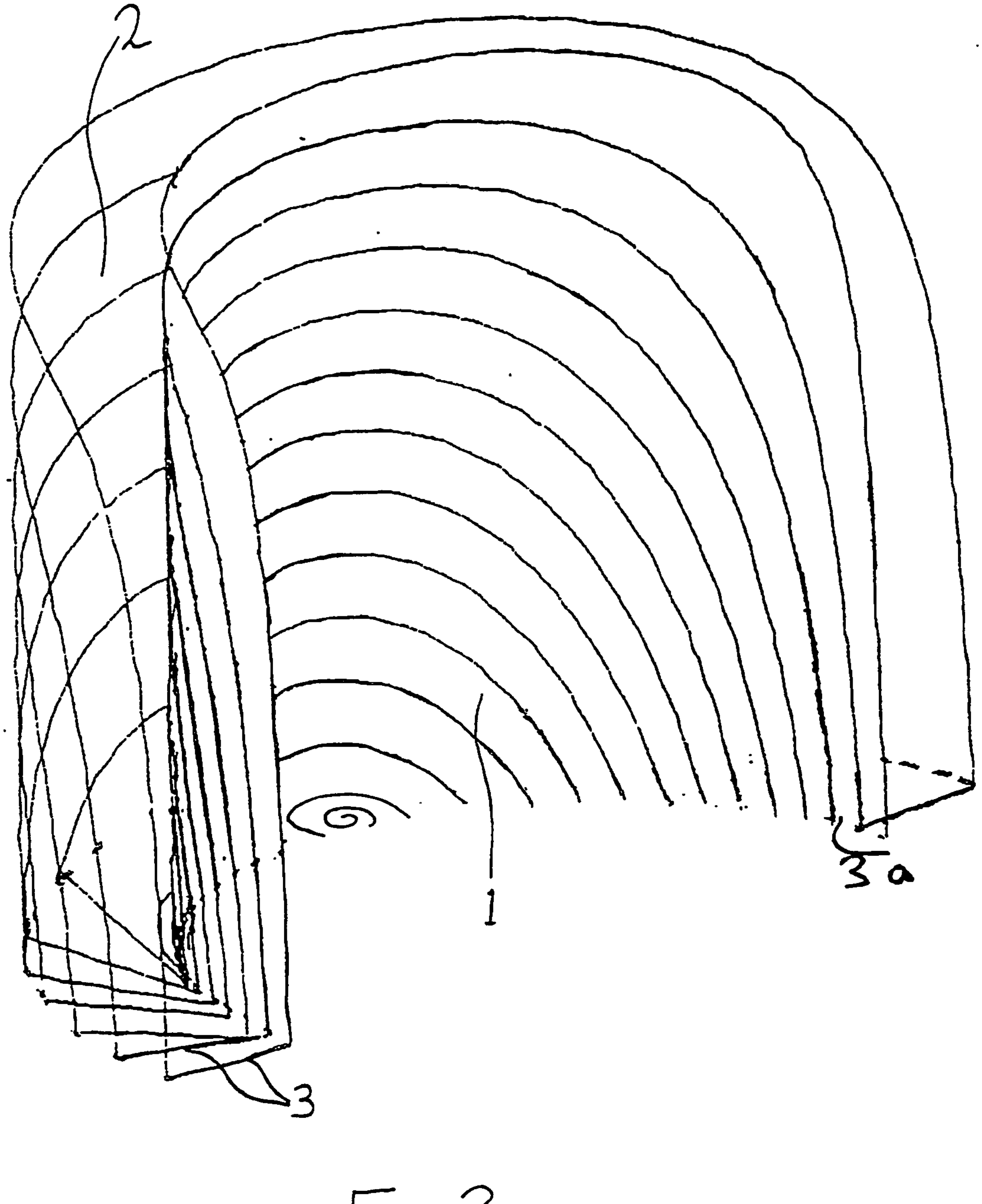

Figure 3a.

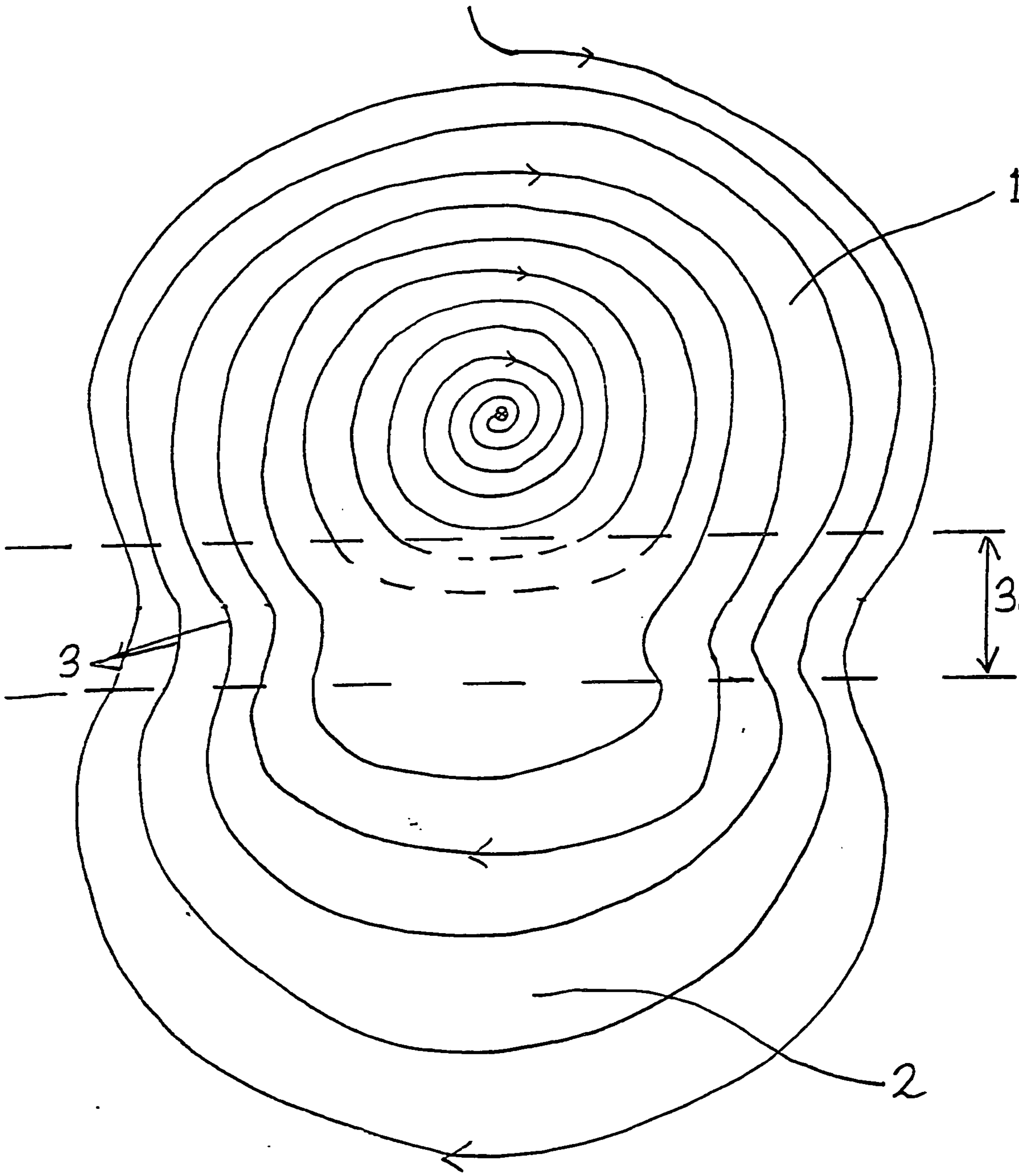

FIGURE 3b

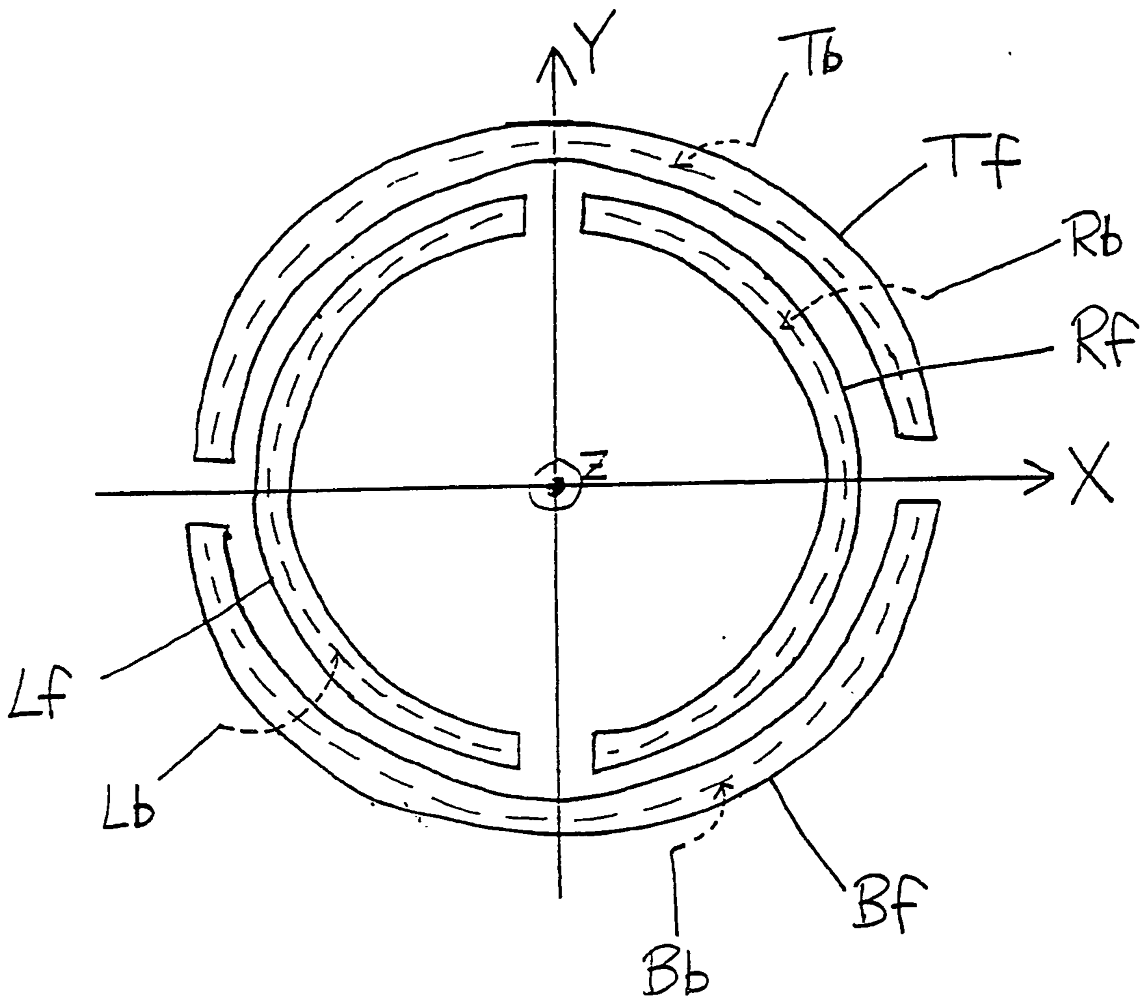

Figure 4.

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A Gradient Coil for Magnetic Resonance Imaging in Axial Magnets

The present invention relates to techniques of Magnetic Resonance Imaging (MRI), and of Localised Magnetic Resonance Spectroscopy (Localised-MRS) and more particularly to improvements in coil configuration for generating the gradient fields commonly used to modulate the main magnetic field in order to provide spatial information.

One commonly used configuration for MRI/MRS employs a cylindrically symmetric "solenoidal" electromagnet generating a central zone of highly homogeneous axial magnetic field. The nuclear spins of suitable substances become aligned in the field, and by appropriate radio-frequency stimulation, can be made to give off a radio signal at a frequency proportional to the local magnetic field. In order to obtain spatial information, it is necessary to modulate the phase and precession frequency of the spins in a variety of ways, by temporarily altering the local field strength. Gradient coils, normally located on one or more cylinders inside the magnet, perform this function. Three gradient coils are usually employed, generating a gradient in B_z, (the axial component of field) proportional to the Cartesian coordinates x, y, and z respectively. The coils themselves are referred to conventionally as "X", "Y" and "Z" gradient coils. "Z" gradient coils are not covered by the present invention.

Recently more complex imaging techniques have been developed, demanding higher gradient strength and shorter gradient rise-time. To generate such gradient pulses, a set of high voltage, high current power supplies is needed to transfer energy rapidly into the gradient magnetic field. The peak voltage and peak current available may be regarded as the primary

specifications of the power supplies. (In addition the techniques of MRI impose a series of secondary constraints, such as high linearity, high stability, DC coupling and a bandwidth of up to 10kHz). The primary specifications of the power supplies are best defined in terms of the maximum instantaneous power ($V_{max} I_{max}$) required to transfer energy to the magnetic field in the time available.

$$V_{max} x I_{max} = \frac{1}{\text{efficiency}} x \frac{(\text{Peak gradient strength})^2}{\text{Rise-time}} \qquad (1)$$

The term "Efficiency" above is defined as

$$\text{Efficiency} = \frac{(\text{Strength per Amp})^2}{\text{Inductance}} \qquad (2)$$

A given coil design may be discretised in many different ways, but "Efficiency", as defined above, is approximately independent of the number (N) of turns chosen; (Strength-per-Amp N, Inductance N^2)
On the other hand, "Efficiency" is a very rapid function of the scale on which the design is implemented;

$$\text{Efficiency} \quad \frac{1}{(\text{Scale})^5} \qquad (3)$$

so it is desirable to minimise the dimensions of the coil as far as is consistent with considerations of patient access and field linearity.

Previously proposed designs of coil to generate the X and Y gradient field distributions within an axial main magnetic field fall into two main classes, namely "unshielded" and "self-shielded" configurations. Within each of these classes several variations are found, corresponding to a range of design approaches. Typically, however, an unshielded coil consists of four "saddle-coils", each saddle-coil being a spiral of a conductive material, disposed symmetrically on the surface of a cylinder (Fig. 1), and connected in series,

in such a way that current in all the central arcs flows in the same direction in space. This configuration generates a gradient in the axial component of field in the enclosed region.

In order to generate X- and Y-gradients in the axial component of field, there are typically two sets of four such saddle-coils each disposed on the surface of a cylinder. It is possible for the cylinder to be divided into four quadrants about its axis, the coils for generating the X-gradient being within a first and third quadrant of the cylinder while the coils for generating the Y-gradient would be within the second and fourth quadrants of the cylinder. The X-gradient coils are not necessarily on a cylinder of the same radius as that of the Y-gradient coils. Instead, it is more usual for the two sets of coils to be disposed on two concentric cylinders of different radius, in which case the coils are not each limited to being within a quadrant of a cylinder. The cylinders are generally of similar radius in the interests of uniformity of the gradient fields.

In order to explain the 'self-shielded' configuration of gradient coil, a single gradient coil of the arrangement shown in figure 1 will again be considered in order to simplify the explanation and drawings. Such a coil would be suitable for generating an X- and Y-gradient, and two such sets of coils, arranged in the manner explained in the previous paragraph, would be required to generate X- and Y-gradients.

A self-shielded coil (Fig. 2) normally consists of two such cylindrical arrangements of saddles, one inside the other. The outer set of coils is connected in "anti-series" with the inner set, so that a negligible amount of stray flux escapes beyond the outer cylinder. This arrangement minimises inductive eddy-current interactions with the magnet's

structure, which otherwise (as in the case of unshielded coils) cause disruptive, time-varying magnetic fields in the imaging region. The precise pattern that the inner and outer windings should follow is arrived at by a variety of complex calculations that are disclosed in GB-A-2,221,540.

A range of evolutionary variations of the configuration described above is possible, such as the use of non-cylindrical formers. However, such configurations are difficult to manufacture, and are not in common use.

As Equation (1) implies, the power required to achieve a specified gradient performance is proportional to the total energy in the gradient's magnetic field, and inversely proportional to the time available to energise it. Only the first of these is open to modification by altering the design. However gradient coils designed on given radii, tend to have similar efficiencies (say within a factor of two). Stored energy can be reduced in four main ways;

1) By eliminating "bunching" of turns, using distributed windings.

2) By reducing the overall length of the inner saddles, a process that is eventually limited by the degradation of coil linearity it causes.

3) In the case of self-shielded coils, by keeping the ratio of the outer and inner radii as high as possible, to reduce the value of flux density in the gap between the two cylinders. As local energy density is proportional to the square of the flux density, and the total flux involved is more or less fixed, it is of benefit to keep the gap between the cylinders as large as practicable.

4) By scaling down the gradient, in accordance with equation (3). This is by far the most ffective measure, but is limited by considerations of access, and by the degradation in linearity that results. In

particular cases, (such as imaging of the human brain) the length of the coil set, rather than its diameter, may be the limiting factor, due in this case to interference with the shoulders.

When all these steps have been taken to the best of the designer's ability, the relationship between gradient set performance and drive-power required approaches a plateau, for a given set of constraints. The instantaneous power levels involved are considerable, expressible in tens, hundreds, or even thousands of kilowatts.

The present invention provides a gradient coil unit for an X- or Y- gradient coil of a magnetic resonance imaging apparatus, said unit being a folded spiral of an electrically conductive material, wherein

the unit includes a first set of loops of conductive material disposed on an inner curved surface and a second set of loops of conductive material disposed on an outer curved surface, and wherein

selected loops of the outermost part of the first set of loops are connected to selected loops of the second set of loops by loop-connect parts extending between the curved surfaces at the fold.

In order that the present invention be more readily understood an embodiment thereof will now be described by way of example with reference to the accompanying drawings, in which:-

Fig. 1 is a diagrammatic perspective view of a conventional, unshielded X or Y gradient coil;

Fig. 2 is a diagrammatic perspective view of a conventional self-shielded coil gradient with a part removed for clarity;

Fig. 3a is a diagrammatic perspective view of a part of an X or Y gradient coil according to the present invention

Fig. 3b is a diagram showing the part shown in Fig. 3a but unfolded; and

Figure 4 is a diagram showing an arrangement of eight gradient coil units of the type shown in figure 3 for generating an X- and a Y-gradient in an axial field.

A part of an X or Y gradient coil is shown in Fig. 3 where an inner partial saddle 1 and an outer partial saddle 2 are located on the cylindrical surfaces of a finite annulus. The partial saddles 1 and 2 are inter-connected by "spokes" 3 on one end surface of the annulus.

The coil unit shown in figure 3 represents a quarter of a full X- or Y-gradient coil, which would replace one of the conventional self-shielded gradient coils shown in Figure 2. In use there would in general be at least eight gradient coil units of the type shown in Figure 3, including four comprising an X-gradient coil and four comprising a Y-gradient coil. A typical arrangement of units is represented in Figure 4, in which X- and Y-gradient coils are viewed in the direction of the Z axis, along the axis of the cylinders. Each approximately semicircular crescent represents a coil half comprising two units as shown in Figure 3, having an inner part and an outer, particularly inter-connected outer part. Those shown in full (Tf,Bf,Rf,Lf) represent the front four units; those shown by dotted lines (Tb,Bb,Rb,Lb) represent the back four units. Each coil half is constructed from two coil units with their arches adjacent and their end surfaces 3a forming the ends of the coil half.

In order to describe a possible arrangement of the wirings in a gradient coil according to the present invention, reference is made to Figure 3, which shows a single gradient coil unit, for the sake of clarity. It may be helpful to think of this configuration as being like a position of the cuff of a sleeve, rolled back on

itself. Unrolled, the wiring would be in the form of an irregular spiral, the turns of which would be more closely spaced one side of the centre than the other. When rolling the 'cuff' back on itself, the line of the fold would be through the spiral a sufficient distance from the centre of the spiral to leave several complete turns of the spiral on the inside of the 'cuff'. The result is an inner saddle portion 1 is a part of a series-wound self shielded set and has more turns than the outer saddle portion 2. It is therefore necessary to leave some of the inner turns unbroken.

The interconnection method described above is extremely ad-hoc. By comparison with a conventional self-shielded coil, both linearity and shielding efficiency will be compromised, but by choosing a suitable truncation boundary, this degradation can be kept within acceptable limits.

The present invention takes advantage of the fact that X and Y gradients are generated primarily by the coils' central turns, and that the coils' return arcs are less efficient (or counter-productive) at generating central gradients, while they contribute to the total stored energy of the coil.

Another way to look at the present invention is to consider a conventional self-shielded design on two cylinders. The current density on the outer cylinder will replicate the eddy current distribution on a conducting cylinder at the same position. If we now imagine the effect of distorting the ends of the inner cylinder outward in some sort of "shoulder" configuration, until it meets the shield coil, the optimum current distribution in the ends of the shield coil will be equal and opposite to that in the larger diameter section of the "inner coil". In other words, the coincident regions of the inner and outer coils might as well not be there. We can remove them and

stitch together the current in the two coils along the join.

Preferably, an optimisation step is carried out by adjusting current distributions as the inner coil is distorted, so as to maintain coil linearity. This would be mathematically complex, and as a first step, we have adopted an ad-hoc method of coil truncation which still achieves reasonable levels of coil linearity. We take an existing self-shielded design and truncate it at $\pm Z_{trunc}$ to form a finite annulus. We are left with n_{inner} and n_{outer} arcs of each inner and outer saddle ($n_{inner} > n_{outer}$). Where possible, inner and outer arcs are linked on the end-faces of the annulus. Those ($n_{inner} - n_{outer}$) inner arcs left over are closed on the end face.

Various modifications can be made to the coils units as shown in Fig. 3a. For example, whereas in Fig. 3a all the connections on the end face of the annulus are radial, it is possible for one or more of the loops of the inner set to be connected to its neighbour by a connecting portion extending along the fold on the end surface as shown in dotted lines in Fig. 3b.

Further, the outer set of loops can be separated into two groups, one group being directed generally as shown in Fig. 3a but the other group extending generally in the opposite direction from the end surface. Either or both of the coil units of each coil half can be arranged in this manner.

Depending on the shape of gradient it is desired to produce, the spiral of each coil unit can be altered from the one shown in Fig. 3b.

The present invention has greater efficiency than conventional X/Y self-shielded gradient coils. This is achieved in two ways, which can be described as "direct" and "indirect". The direct effect is that, compared to the parent self-shielded coil, the inductance is roughly halved while the strength p r amp

is barely altered. Therefore to achieve a given level of performance (peak strength and rise time) only half as many gradient amplifiers are needed. The indirect effect is that, in certain configurations (eg. head-imaging) the reduced length-to-diameter ratio of this design permits the coil set to be scaled down, (as the shoulders do not have to be accommodated) with a consequent $(\text{Scale})^{-5}$ increase in efficiency.

The consequence of the increased efficiency cited above is that a given level of performance can be achieved using fewer or less powerful gradient amplifiers.

A subsidiary advantage, not to be confused with those mentioned above, is that of reduced dissipation, due to the shorter winding length of the coil. This reduces power consumption, and eases the extraction of heat from the coil set.

The primary feature of the invention that is believed to be new is that of multiply linking the inner and outer segments of self-shielded X/Y gradient set, in each case replacing a pair of substantially distinct saddles with "folded saddle". This results in a low value of the length:(inner diameter) ratio that can be achieved while retaining reasonable linearity.

The improved access the coil provides for imaging of extremities of the larger object or patient. All the above advantages are achieved simply by the improved coil construction and not by changes to the drive electronics which are basically conventional.

CLAIMS:

1. A gradient coil unit for an X- or Y- gradient coil of a magnetic resonance imaging apparatus, said unit being a folded spiral of an electrically conductive material, wherein

the unit includes a first set of loops of conductive material disposed on an inner curved surface and a second set of loops of conductive material disposed on an outer curved surface, and wherein

selected loops of the outermost part of the first set of loops are connected to selected loops of the second set of loops by loop-connector parts extending between the curved surfaces at the fold.

2. A gradient coil unit according to claim 1 wherein at least one loop of the first set of loops is connected to another loop of the first set of loops by a loop-connector portion extending along the fold.

3. A gradient coil unit according to claim 1 or 2 wherein the spiral is an irregular spiral so that the first set of loops includes a plurality of complete revolutions.

4. A gradient coil unit according to claim 1, 2, or 3 wherein at least a selected loop of the second set of loops is aligned in a direction whereby current flowing along the spiral of conductive material flows in the selected loop in a direction substantially opposite to that in which it flows in non-selected loops of the second set of loops.

5. A gradient coil unit according to any of the preceding claims wherein said inner and outer curved surfaces are parts of two substantially concentric cylinders.

6. A gradient coil unit according to any of the preceding claims wherein said inner and outer curved surfaces are adjacent to each other.

7. A gradient coil for generating an X- or a Y-gradient in an axial magnetic field of a magnetic resonance imaging apparatus, said coil comprising a plurality of gradient coil units of the type described in any of claims 1 to 6.

8. A gradient coil according to claim 7 comprising four gradient coil units of the type described in any of claims 1 to 6 arranged on a pair of substantially cylindrical surfaces, wherein the folds of a first pair of gradient coil units form a substantial part of an annulus at one end of the pair of surfaces and the folds of a second pair of gradient coil units form a substantial part of an annulus at an opposite end of the pair of surfaces.

9. An apparatus for generating X- and Y-gradients in an axial magnetic field of a magnetic resonance imaging apparatus comprising a pair of gradient coils of the type described in claim 7 or 8, wherein a first gradient coil is oriented for generating an X- gradient and second gradient coil is oriented for generating a Y- gradient.

10. An apparatus according to claim 9 wherein the first gradient coil is disposed on a first pair of substantially cylindrical surfaces and the second gradient coil is disposed on a second pair of substantially cylindrical surfaces, wherein the first and second pairs of surfaces are concentric.

11. A gradient coil unit substantially as hereinbefore described with reference to the accompanying drawings.

12. A gradient coil substantially as hereinbefore described with reference to the accompanying drawings.

13. An apparatus for generating X- and Y-gradients in an axial magnetic field of a magnetic resonance imaging apparatus substantially as hereinbefore described with reference to the accompanying drawings.

Patents Act 1977
Examiner's report to the Comptroller under Section 17 (The Search Report)

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Relevant Technical fields

(i) UK Cl (Edition L) G1N

(ii) Int Cl (Edition 5) G01R (33/38,33/42)

Databases (see over)

(i) UK Patent Office

(ii)

Search Examiner

K SYLVAN

Date of Search

21 JUNE 1993

Documents considered relevant following a search in respect of claims 1-13

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
E,X	WO 92/05737 A1 (YOKOGAWA MEDICAL SYSTEMS) 16 April 1992 see Figures 1-3	X:1-3,5-7 10

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

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